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ARE COASTAL PROTECTIVE HARD STRUCTURES STILL APPLICABLE WITH RESPECT TO SHORELINE CHANGES IN SRI LANKA?

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Abstract

Monitoring the changes in coastlines is an important matter and has been the subject of great concern in recent years. The Western and North-Western provincial coasts of Sri Lanka are economically significant and have a highly dynamic nature. This study used satellite images from the Google Earth platform to analyze the changes occurring in the coastal zone during the period between 2005 and 2019 on the Western and North-Western provincial coasts of Sri Lanka. The results revealed that the average coastal erosion rates are -1.21 ± 0.04 m yr^{-1} in Kalutara, -0.54 ± 0.63 m yr^{-1} in Colombo, and -0.7 ± 0.58 m yr^{-1} in Gampaha district. Puttalam district showed a 0.26 ± 0.07 m yr^{-1} average accretion rate, while the highest accretion rate (0.95 ± 0.58 m yr^{-1}) was evident in the coastal region of Wilpattu National Park, an area that has few anthropogenic interventions. The application of hard structures to mitigate the effect of coastal erosion has increased within the past 15 years. At the end of 2019, the country mainly used revetments up to 23,554 m in length (occupying 9.05% of the total study area), consisting of 18,960 m in the Western province (7.29%) and 4,594 m in the North-Western province (1.76%). The Western province has applied more hard structures at a higher rate than the North-Western province due to mega-development projects. Overall, anthropogenic activities are affecting coastal erosion in that area more than natural or global scenarios, and the applied hard structures have little capability to control erosion.

Keywords: coastal hard structures, erosion, accretion, anthropogenic impacts, shoreline

JEL Classification: Q20, Q53, Q57

Contents

1. INTRODUCTION

Sorenson and McCreary (Clark 1995) defined a coastal zone, or a coastal area, as the transition or interface region where "part of the land is affected by its proximity to the sea and where part of the ocean is affected by its proximity to the land." The Coast Conservation Act of 1981 defined the coastal zone of Sri Lanka as follows:

> *… the area lying within a limit of 300m landward of the mean high-water level and a limit of 2 km seaward of the mean low water level. In the case of rivers, streams, lagoons, or any other body of water connected to the sea either permanently or periodically the landward boundary extends to a limit of 2 km measured perpendicular to the straight base line drawn between the natural entrance points thereof and shall include the waters of such rivers, streams, and lagoons or any other body of water so connected to the sea.*

It is a complex series of interlinked physical systems that involve both offshore and onshore processes (Prasad and Kumar 2014).

In fact, coastal zones are very important due to their abundant natural resources and wide variety of interconnected ecosystems, such as coral reefs, seagrass beds, mangroves, sand dunes, coastal vegetation, lagoons, estuaries, and coastal wetlands (Clark 1995; Alesheikh, Ghorbanali, and Nouri 2007). As Sri Lanka is a small island, the coastal zone is a remarkable landscape that plays a vital role in the country's economy. The development activities covering the fisheries sector, tourism and transport, and logistic development provide unlimited benefits to the coastal dwellers over a wide area. Therefore, most countries distinguish their coastal zone as a key element of their economy and culture (Clark 1995; Beatley, Brower, and Schwab 2002).

Research has identified coastal erosion and temporal shoreline changes as a major national-level problem in this developing country since the early 1980s (Perera 1990; Godage 1992). The temporal shoreline changes resulting from natural phenomena like coastal floods, storm surges, hurricanes, tsunamis, sea-level rises, and tidal variations could cause coastal erosion (Zhang, Douglas, and Leatherman 2004; Prasetya 2006; Nayak 2017). Research has found that coastal longshore currents, coastal rip currents, waves, and wind activities, transporting sand from the shore and depositing it somewhere else, are influential factors for coastal erosion (Senevirathna et al. 2018). In addition, amplified anthropogenic activities, such as disturbing coral reefs, sand mining, deforesting coastal vegetation, and artificial alteration through dredging, filling, and construction, are leading issues that produce coastal erosion (Clark 1995; Van Rijn 2011; Prasad and Kumar 2014). Coastal erosion directly and indirectly creates environmental issues, reduces economic growth, and generates social conflicts (Hanson and Lindh 1993; Ndour et al. 2018; Williams, Rangel-Buitrago, Pranzini, and Anfuso 2018).

Researchers identified coastal erosion as a major problem a long time ago. The mechanisms of coastal erosion are not fully understood, and researchers have not fully investigated the effect of coastal protective structures. As a developing country, Sri Lanka has implemented various types of coastal protective methods. The major techniques that it has used to protect its coastal areas are soft coastal protection techniques (beach nourishment and dune construction) and hard coastal protection techniques (revetments, groynes, offshore breakwaters, gabion walls, coves, and immediate rock beddings), which allow the shore to behave naturally without any constructive protection method (declared as a restricted area) (Dias, Ferreira, Matias, Vila-Concejo, and Sá-Pires 2003; Iskander 2010; Borsje et al. 2011). However, a new inclination toward eco-friendly, soft, and state-of-the-art methods rather than hard constructions is observable (Hegde 2010). Due to the prevailing economic state of the country, it has implemented low-cost coastal protective structures, and research has not yet fully studied their effectiveness and their negative impacts on the coastal zone of Sri Lanka.

On the other hand, the monitoring of coastal zones is a significant task in sustainable development and environmental protection due to their highly dynamic nature; they are continually changing due to the interaction between the oceans and the land (Harley, Turner, Short, and Ranasinghe 2011; Łabuz 2015) and various anthropogenic impacts (Dias, Ferreira, Matias, Vila-Concejo, and Sá-Pires 2013; Pessoa and Lidon 2013). Therefore, conducting regular monitoring of the coastal environment is very important to ascertain the environmental, social, and economic vulnerabilities in the coastal regions.

Furthermore, several major economic activities take place in the coastal zone, like tourism, fisheries, fishery harbors, commercial harbors, and development projects, such as power generation projects, and approximately 70% of tourist hotels and nearly 62% of industrial units contribute to the national gross domestic product (GDP) (Coastal Zone Management Plan (CZMP) 2004). Furthermore, the rapid development of infrastructures has occurred with the high densification of inhabitants along the coastal zone within the past decades (Senevirathna, Edirisooriya, Uluwaduge, and Wijerathna 2018).

The geographical information system (GIS) and remote sensing (RS) technology are among the dominant tools for quantifying the changes in the coastal zone with shoreline change as they provide information in digital form (Zuzek, Nairn, and Thieme 2003). In addition, researchers have identified GIS and remote sensing techniques using high-resolution satellite images as one of the best solutions to investigate shoreline changes over a long period of time as they are efficient and effective and have access to temporal data (Warnasuriya, Gunaalan, and Gunasekara 2018). The high-resolution satellite images from the Google Earth (GE) platform are freely available, so they are cost-effective and can enable the mapping of changes in a coastal zone after the appropriate corrections. The major advantages of using GE satellite images are the availability of both medium- and high-resolution images and the availability of time series data (Malarvizhi, Kumar, and Porchelvan 2016).

Recent studies have revealed that the erosion of the coastal zone of Sri Lanka is a long-standing problem (Lakmali et al. 2017; Ratnayake et al. 2018, 2019) but has poor monitoring and documentation. Other than that, studies on shoreline changes have been very limited in the Western and North-Western provinces.

The Western coastal area (Kalutara, Colombo, and Gampaha districts) of Sri Lanka has a highly concentrated population, development activities, and infrastructures and industries, including the capital city of Colombo, with mass development projects that will increase the coastal erosion of their particular area. The North-Western province's coastal zone includes only the Puttalam district, which covers the Willpattu National Park. Its status as a restricted area that belongs to the national park fully inhibits anthropogenic interventions.

The current study selected the Western coastal area (Kalutara, Colombo, and Gampaha districts)—Zone A—and the North-Western coastal area (Puttalam)—Zone B—to study the temporal shoreline changes over a 15-year (2005–2019) time period. To determine the effectiveness of the applied coastal protective structures and the effect of the physical alteration due to anthropogenic interventions and natural phenomena, it investigated the shoreline changes over the 15-year period by utilizing GIS and remote sensing techniques.

2. MATERIALS AND METHODS

2.1 Study Area

The coastlines of three administrative districts, specifically Kalutara (42.3 km), Colombo (24.3 km), and Gampaha (34.7 km), belong to the Western province (Zone A), while only the coastline of Puttalam district (159 km) belongs to the North-Western province (Zone B). The study area extends approximately 260 km in the coastal zone from the Bentota River (Western province), Kalutara, to the Modaragam-aru River, Puttalam (North-Western province). This area Lies between the Benthota River, at the Southern End of Kalutara (6.5854° N, 79.9607° E), and the Modaragam-aru River, at the Northern End of Puttalam (8.0408° N, 79.8394° E).

The study area experiences a typical maritime climate with an average temperature of 27 °C on the western and north-western coasts. The mean annual rainfall varies from less than 900 mm in the driest parts (North-Western province) to over 5,000 mm in the wettest parts (Western province) (Schott and McCreary 2001; Tomczak and Godfrey 2013; Department of Meteorology, Sri Lanka 2019). The rainfall pattern varies seasonally with the monsoon system. The prevailing changes in the weather are due to the south-western monsoon (May to September) (Ranathunge et al. 2003). The changes in the sediment transport flux, river discharge, and wave climate are totally dependent on the monsoon pattern, and it directly influences the temporal coastal changes. The area faces numerous natural hazards, such as coastal erosion, stream flooding, storm and tidal surges, and active surface faulting. The anthropogenic interventions include sand mining, coral mining, coastal development, inappropriate removal of coastal vegetation, and direct pollution as well as temporal coastal changes. The Wilpattu National Park, a protected area, completely covers Zone B, which represents the Wilpattu region (from Dutch Bay to Modaragam-Aru—26 km). Because of that, there are no interventions from humans. The topography of the beach area includes rocky cliffs, dunes, and the main beach area, for which coastal vegetation forms a boundary. The rocky cliffs, dunes, and coastal vegetation act as barriers as well as natural protectors of the coast (Tien and Sam 2007).

The categorization of the considered topographical changes includes temporal shoreline change, applied coastal constructions (protective barriers/hard protection techniques), and coastal developments through physical alteration of the shoreline in each district, Kalutara, Colombo, and Gampaha (Zone A) and Puttalam (Zone B).

2.2 Data Collection and Data Processing

The study used high-resolution satellite images to extract shorelines through the digitization of multi-date satellite images to form the shape files. It extracted the coastal constructions/alterations (e.g., harbors, artificial coastal islands, etc.) and coastal protective structures (revetments, groynes, breakwaters, and coves) throughout the 15-year period from 2005 to 2019 by using the Google Earth Pro 7.3 software package.

The study detected the temporal shoreline positions and physical alterations, including the coastal constructions/alterations and coastal protection structures, through both visual interpretation and manual declination using the Google Earth Pro 7.3 software package. It incorporated satellite images, community-based interviews, previous construction data from the Coast Conservation and Coastal Resource Management Department of Sri Lanka (CC and CRMD), and published documents wherever necessary for validation.

2.2.1 Extraction of the Shoreline

The study considered the borderline between land and water as the shoreline, referencing the blue margin that splits the land from the water in satellite images via visual interpretation (Warnasuriya, Gunaalan, and Gunasekara 2018; Warnasuriya, Kumara, Gunasekara, Gunaalan, and Jayathilaka 2020). The wave action within the selected season of the years (October, November, December) was comparatively low because there was no direct influence of the inter-monsoon (October–November) and north-east monsoon (December–February) on the study area (Schott and McCreary 2001; Gunaratna et al. 2011; Tomczak and Godfrey 2013; Thevasiyani and Perera 2014; Bamunawala et al. 2015).

Table 1: Approximate Spatial Resolution of the High-Resolution Satellite Images from the Google Earth Platform

Date	Approximate Spatial Resolution (m)
Dec. 2005	0.31–1.84
Dec. 2010	0.31–1.84
Nov. 2015	0.31–1.84
Dec. 2019	0.31–1.84

Note: The study used data sources and visual interpretation of GE images by distinguishing the minimum possible identifiable objects to determine the approximate spatial resolution.

Ground truth investigation obtained ground control points (GCPs) in places; physical shoreline alteration with protective structures affected shoreline positions and permanent structures (harbors and buildings) and adjusted ecosystems (sand dunes and vegetation). The ground survey obtained GCP locations using the Garmin GPSMAP 64s Global Positioning System (GPS).

In the shoreline extraction, the tilt of the images of the study area, the scale, and the eye altitude (300 m) remained similar for each image throughout the process to remove the errors arising during digitization due to the zoom level (Warnasuriya, Kumara, Gunasekara, Gunaalan, and Jayathilaka 2020). The authors saved the digitized shorelines in Keyhole Markup Language (KML) file format and converted the KML files into "layer files" using the ArcGIS 10.6 software. They projected all the digitized shorelines to the WGS 1984 UTM 44N projection system.

2.2.2 Shoreline Rectification

The authors checked the accuracy of the satellite images using 15 GCPs and applied geometric corrections to each shoreline before conducting the analysis process (Figure 1). They estimated slight shifts of GE satellite images due to geo-referencing errors and platform-oriented errors with reference to the GCPs in the satellite image of 2011, which was closely related to the ground truth data (Warnasuriya, Gunaalan, and Gunasekara 2018). These authors considered permanent structures, such as the roof tips of square-shaped buildings, as GCPs in all the satellite images of different years.

Figure 1: Selected Ground Control Points (GCPs)
(from Bentota River, Kalutara, to Modaragam River, Puttalam)

Source: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordinance, Survey, Esri Japan, METI, Esri People's Republic of China (Hong Kong, China). ©OpenStreetMap contributors and the GIS User Community.

The respective latitudes and longitudes of each of the 15 GCPs are the following (Table 2); the authors used them to check the accuracy of the satellite images.

Table 2: Coordinates of GCPs Used in Geometric Corrections

Point/Location	Latitude	Longitude
1	6°26'33.04"N	79°59'32.28"E
2	6°32'38.23"N	79°58'40.70"E
3	6°36'34.93"N	79°56'56.12"E
4	6°42'2.68"N	79°55'28.96"E
5	6°43'55.76"N	79°53'49.73"E
6	6°48'7.05"N	79°53'27.25"E
7	6°54'34.19"N	79°53'22.62"E
8	7° 3'57.79"N	79°53'37.48"E
9	7°10'41.90"N	79°51'45.31"E
10	7°17'53.77"N	79°50'27.96"E
11	7°20'53.36"N	79°49'53.08"E
12	7°27'4.50"N	79°48'26.48"E
13	7°29'16.45"N	79°48'5.52"E
14	7°34'40.58"N	79°47'42.60"E
15	7°35'7.70"N	79°47'40.50"E

2.2.3 Shoreline Data Processing

The authors used the "Append (Data Management)" tool to overlay and append all the shorelines to input the datasets into an existing target dataset. After appending, they created buffer polygons with 100 m width for each shoreline and merged the buffer polygons to create the baseline. They managed all these activities in a specific personal geodatabase using the ArcGIS 10.6 software. They created two feature classes to represent the shoreline and baseline in the same geodatabase and used the appended shoreline dataset to create a shoreline feature class; they then used the created buffer polygon to create a baseline feature class with specific attributes.

The study used the standard deviation of the positional shift as the initial uncertainty (U1) and considered the tidal influence as the second uncertainty (U2) to detect shoreline changes. The average tidal variation on the western coast of Sri Lanka is 0.2–0.3m (Wijeratne and Pattiaratchi 2006). Then, the authors calculated the tidal influence on the shoreline:

$$\mathrm{Tan}\Theta = \frac{\text{Average Tide Variation (m)}}{\text{Shoreline Displacement (m)}}$$

where Θ is the average slope angle (Warnasuriya, Gunaalan, and Gunasekara 2018). They calculated the cumulative uncertainty for each shoreline using

U = U1 + U2

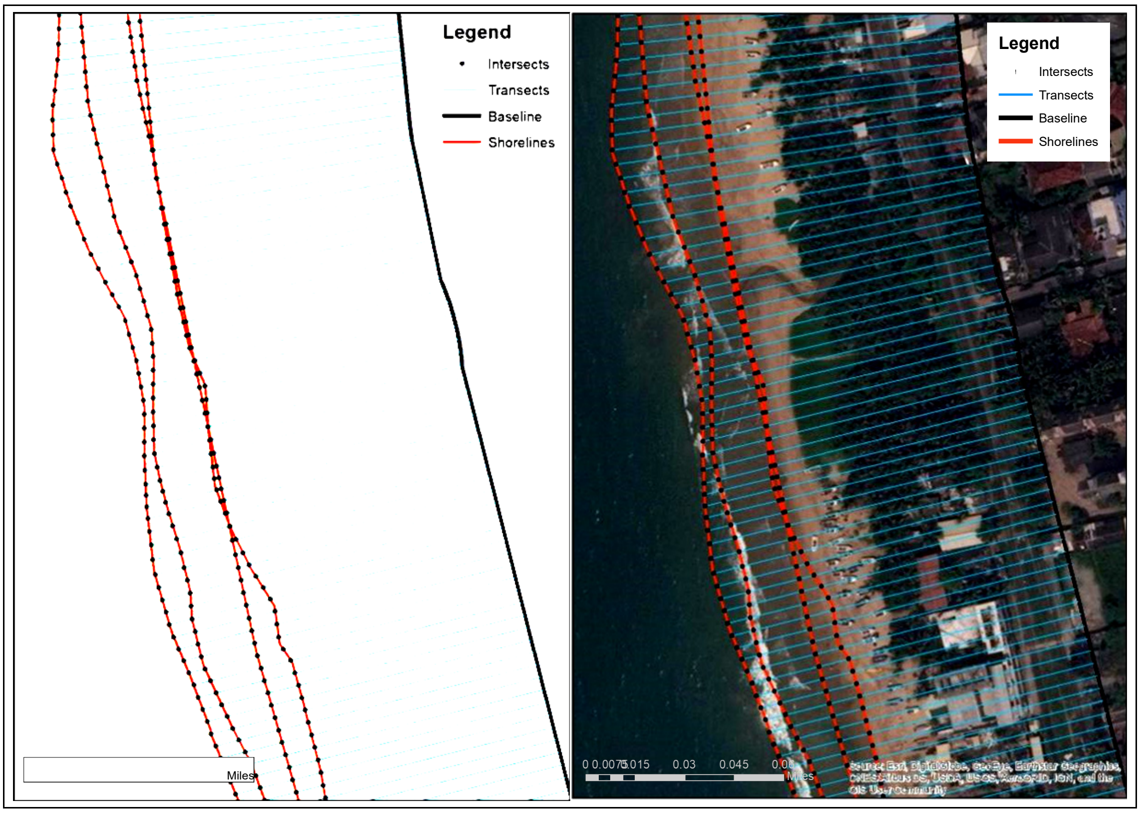
U—cumulative uncertainty

U1—uncertainty due to positional shift (m)

U2—uncertainty due to tidal influence (m)

They used the DSAS version 5.0 tool in the ArcGIS software to calculate the shoreline change statistics. They added the date field and uncertainty field to each shoreline layer and entered the data into the respective attribute tables (for shoreline rectification). Then, they created the "transect layer" by casting transects in 5 m intervals along the baseline, allowing the transects to cross all the shorelines.

Figure 2: Generated Transect Lines from Baseline to Shoreline



Source: Esri, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

2.2.4 Extraction of Coastal Protective Structures

First, the authors adjusted the tilt of the images of the study area using the Google Earth Pro software to minimize the geometric errors and kept the scale similar for each image throughout the digitization process. Then, they delineated the coastal protective structures for the time period from 2005 to 2019 based on the satellite images from the GE platform with the same eye altitude of 300 m. They adjusted these for all the satellite images to avoid errors arising during the digitization process due to the zoom level in the GE software itself.

The authors saved these digitized coastal protective structures in the KML file format year by year. They measured and recorded the length of each coastal protective structure separately according to the following categories:

- Breakwaters
- Groynes (fishtail groyne, roundhead groyne, ‘L’ shaped groyne, ‘T’ shaped groyne)
- Revetments (artificial walls)
- Coves

2.2.5 Extraction of Coastal Developments

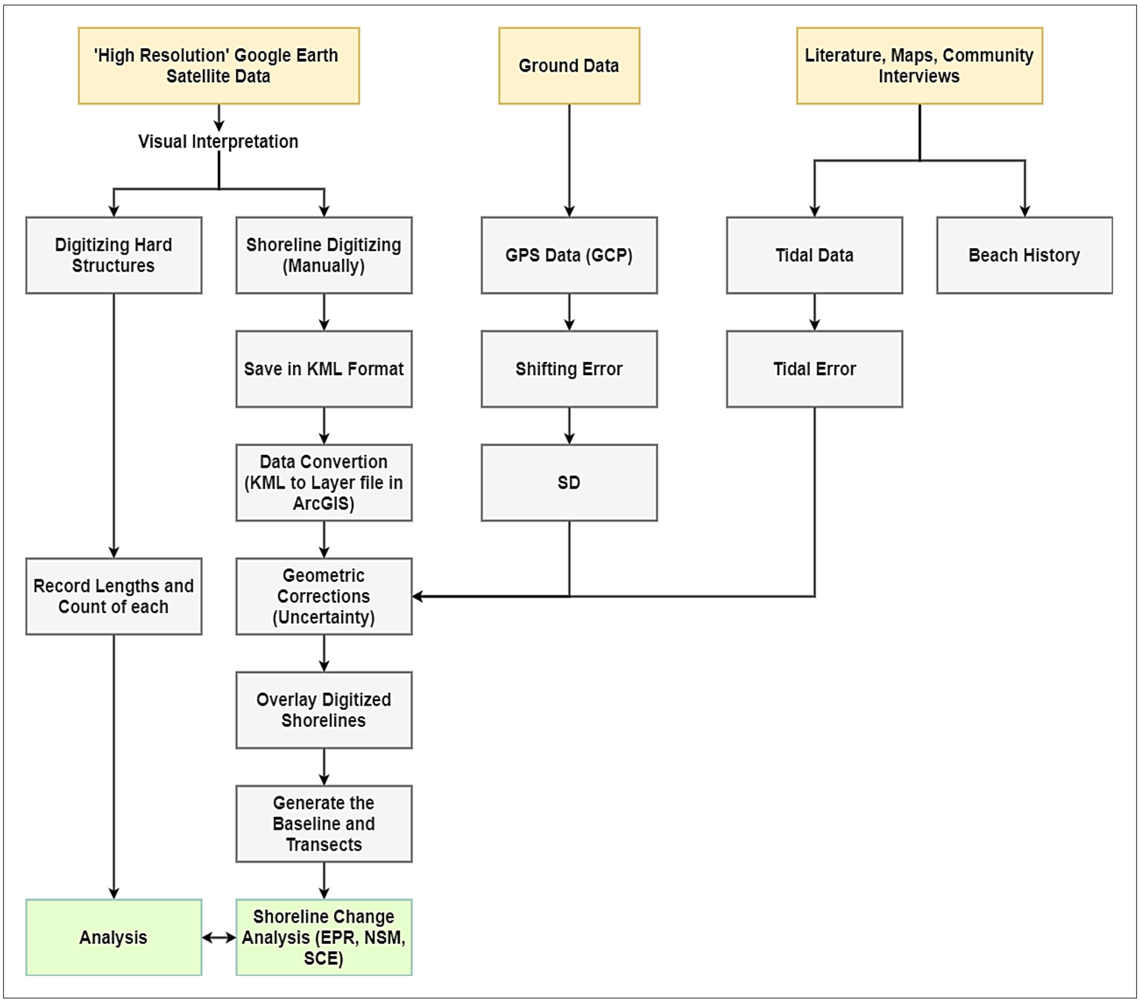
The authors delineated all the coastal developments (harbors/land fillings and coastal protective structures) making physical alterations to the shoreline by digitizing the total area of development within the study area.

2.3 Data Analysis

The net shoreline movement (NSM) explained the distance between the oldest (2005) and the youngest (2019) shoreline (Oyedotun 2014). The NSM revealed the overall shoreline change based on the shoreline position during the 15-year period.

The authors derived the end point rate (EPR) by dividing the distance of the shoreline movement by the time elapsed between the oldest and the youngest shoreline position (Oyedotun 2014). They divided the distance between the oldest (2005) and the youngest (2019) shoreline by the time period of the study. The shoreline change envelope (SCE) is the measurement of the total change of the shoreline positions with their distance without specifying the study dates (Oyedotun 2014; Himmelstoss, Henderson, Kratzmann, and Farris 2018).

Figure 3: Flow Chart Showing the Overall Methodology that the Study Adopted



Note: GPS: Global Positioning System, GCP: Ground Control Points, SD: Standard Deviation, EPR: End Point Rate, NSM: Net Shoreline Movement, SCE: Shoreline Change Envelope.

The DSAS v5.0 tool (extension) in the ArcGIS 10.6 software calculated the shoreline change statistics for the net shoreline movement (NSM), end point rate (EPR), and shoreline change envelope (SCE) to estimate the shoreline changes. MS Excel and the Minitab 17 software analyzed the other results (coastal protective structures, coastal developments, and coastal area). After analyzing the collected data, the authors clarified the relationship between the protective hard structures and the shoreline changes. The study's overall methodology, from data collection and data processing to data analysis, is as follows (Figure 3):

3. RESULTS

3.1 The Shoreline Changes along the Coastal Zone of the Western and North-Western Provinces

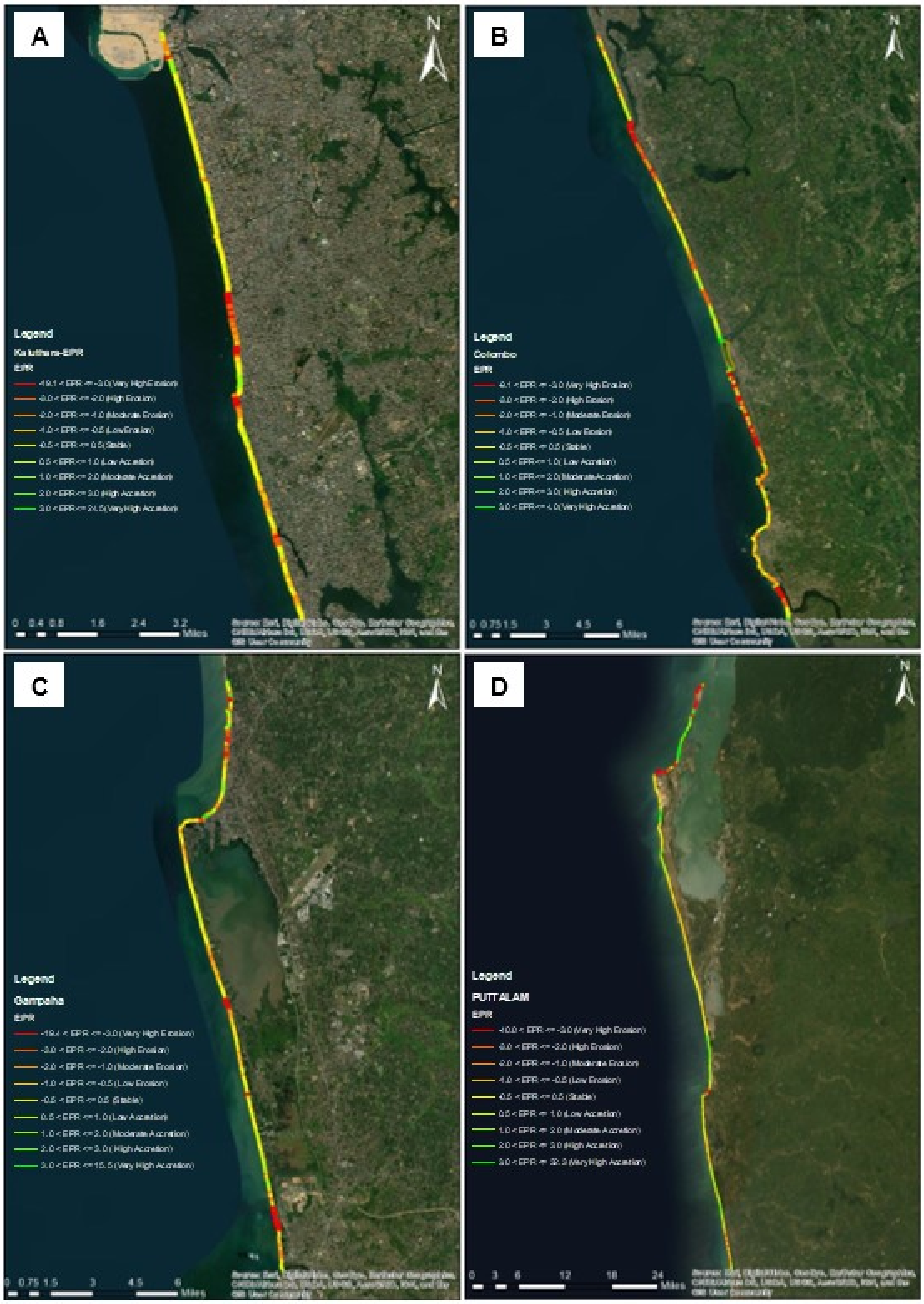
The EPR value shows high variation along the shorelines in the Western and North-Western provinces within the respective study period (Figure 4). The shorelines of the total study area record the distinguished changes in the EPR.

The EPR levels exhibit nine color variations according to the differences in erosion and accretion. The bright red ( ) represents the area that has experienced a very high erosion rate with $X<EPR\leq-3.0$, and the different shades of red represent high erosion ( ) with a $-3.0<EPR\leq-2.0$ rate range, moderate erosion ( ) with a $-1.0<EPR\leq-2.0$ rate range, and low erosion ( ) with a $-1.0<EPR\leq-0.5$ rate range. The yellow ( ) represents the stable condition in the shorelines with a rate of $-0.5<EPR\leq0.5$. The shades of green represent low accretion ( ) with $0.5<EPR\leq1.0$, moderate accretion ( ) with $1.0<EPR\leq2.0$, high accretion ( ) with $2.0<EPR\leq3.0$, and very high accretion ( ) from $3.0<EPR\leq X$, which the bright green represents.

The place with the highest recorded EPR in Kalutara district is Kaluwamodara-West with 24.47 m yr^{-1}. This area is adjacent to the Bentota River estuary, where seasonally washed particles from the upper land form deposits in the estuarine mouth and the adjacent coastal area. The place with the lowest recorded EPR in Kalutara district is Kalutara-South (Katukurunda) with –19.06 m yr^{-1}. The place with the highest recorded EPR in the Colombo district is the Wedikanda-North region with 4.29 m yr^{-1}. The place with the lowest recorded EPR in the Colombo district is the middle part of Mount Lavinia coastline, which recorded –1.93m yr^{-1}.

The place with the highest recorded EPR in Gampaha district is Daluwakotuwa beach, with a 15.47 m yr^{-1} rate, and the place with the lowest recorded EPR in Gampaha district is near Dikowita harbor, with a –6.03m yr^{-1} rate. The place with the highest recorded EPR in Puttlam district is in Kudawa upper division, with 32.3 m yr^{-1}. The place with the lowest recorded EPR in Puttalam district is Kandakuliya, with –39.91 m yr^{-1}.

Figure 4: EPR of the Kalutara (A), Colombo (B), Gampaha (C), and Puttalam (D) Districts and the Wilpattu Region



continued on next page

Figure 4 *continued*

Source: Esri, DigitalGlobe, GeoEye, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

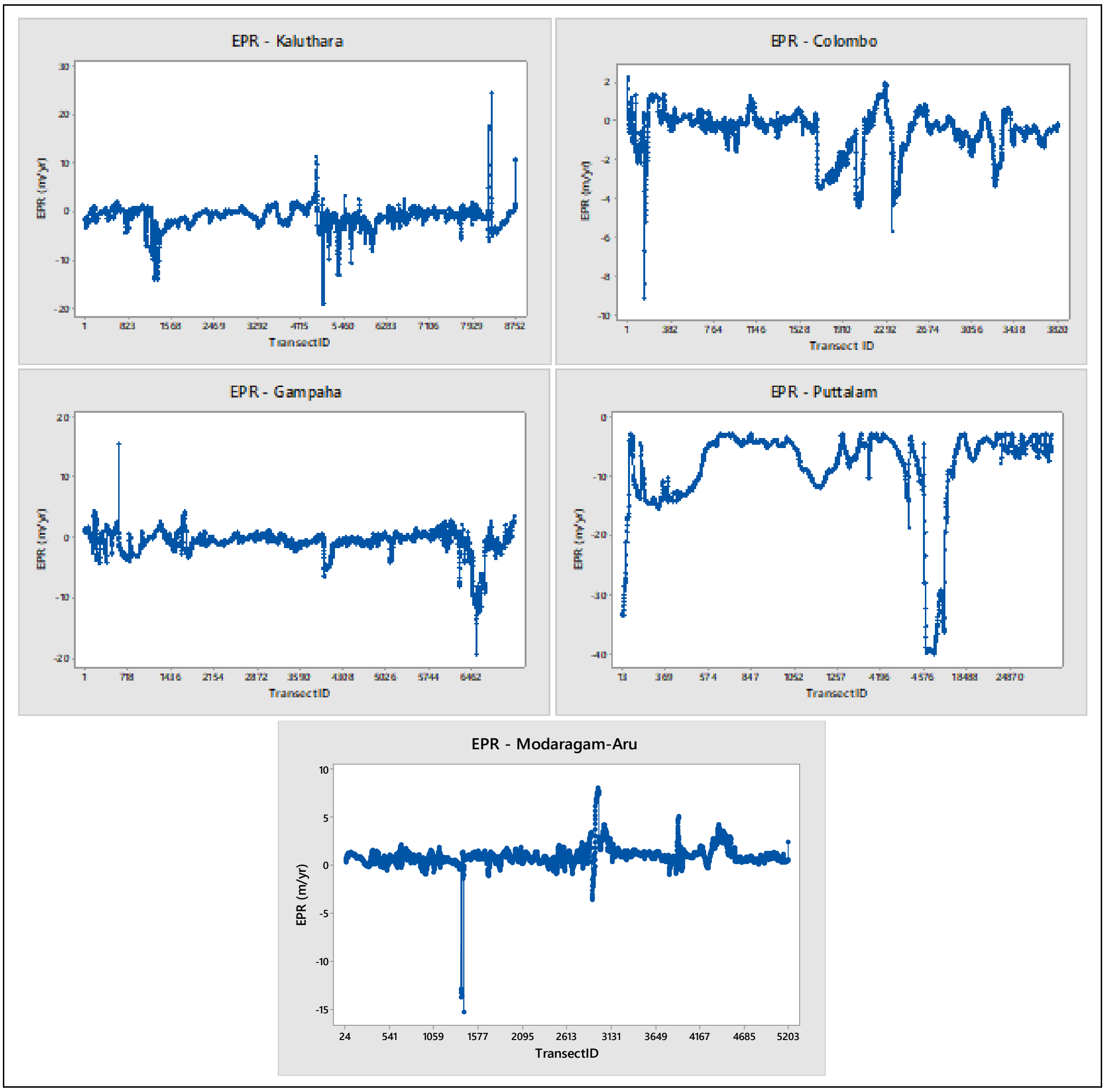
Table 3: Regions with the Largest and Smallest EPR Changes in Each District of the Study Area

			Coordinates (Start)		Coordinates (End)	
District	**Rate**	**Region**	**Lat. (N)**	**Lon. (E)**	**Lat. (N)**	**Lon. (E)**
Kalutara	High	Kaluwamodara	6°33'50.09"	79°59'14.93"	6°26'7.31"	79°59'27.92"
	Low	Katukurunda	6°33'53.75"	79°57'39.49"	6°33'51.37"	79°57'41.40"
Colombo	High	Wedikanda	6°49'58.28"	79°51'40.92"	6°49'50.09"	79°51'42.84"
	Low	Mount Lavinia	6°50'11.03"	79°51'47.10"	6°50'8.92"	79°51'46.19"
Gampaha	High	Daluwakotuwa	7°15'24.47"	79°50'30.34"	7°15'13.97"	79°50'27.27"
	Low	Dikowita	7°0'4.65"	79°52'2.30"	6°59'58.43"	79°52'3.15"
Puttalam	High	Kudawa	8°20'50.77"	79°46'14.20"	8°19'46.57"	79°45'55.70"
	Low	Kandakuliya	8°13'6.66"	79°42'57.00"	8°12'52.08"	79°41'56.93"

As Table 3 shows, the Kudawa upper-division area of Puttalam district shows the highest EPR due to the highest accretion level in the total study area of the Western and North-Western provinces. The Kandakuliya area of Kalpitiya peninsular in Puttalam district shows the lowest EPR due to the highest level of erosion in the total study area of the Western and North-Western provinces. According to Samanmali, Piyadasa, and Wickramasinghe (2014), the Kudawa area of the Kalpitiya peninsular experienced accretion due to sand deposition from 1973 to 2014, and the unconsolidated sand materials created a headland, while the shorelines of adjacent zones moved landward. However, a considerable area of this peninsular was highly dynamic due to wind, wave, and longshore current action (Samanmali, Piyadasa, and Wickramasinghe 2014; Senevirathne, Edirisooriya, Uluwaduge, and Wijerathna 2017). The highest EPR due to erosion observable in this particular area is erosion of this unstable headland.

Figure 5 shows the significant variation in the EPR value due to the Transact ID during the 15-year time period in each study area.

Figure 5: Graphical Representation of the EPR of Kalutara, Colombo, Gampaha, and Puttalam Districts and Wilpattu (Modaragam-aru to Dutch Bay) Region

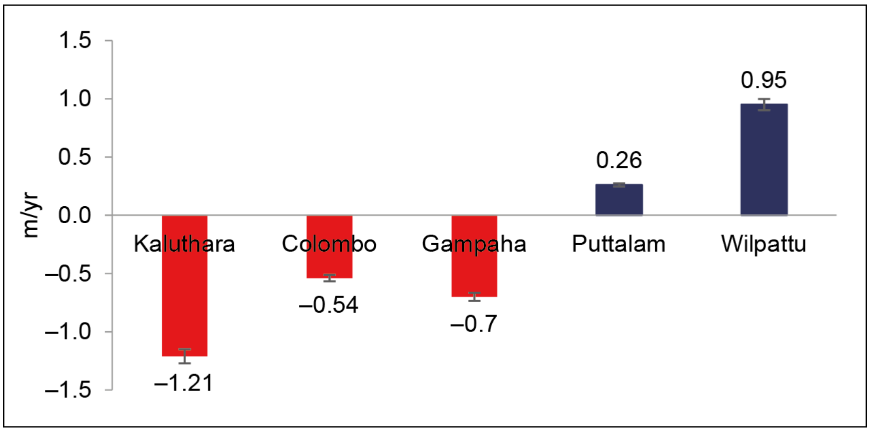


The coastal area of Wilpattu region, the region between the Modaragam-aru River and the Dutch Bay, has fewer human interventions, based on the ground truth investigation and secondary data from the CC and CRM Department, than the Kalutara, Gampaha, Colombo, and Puttalam districts. The output results show that there is a majorly stable and accreted coastal zone in the Wilpattu region, which belongs to Wilpattu National Park. Notably, the high loss of the coastal zone has influenced the Kudiramalei point area of the Wilpattu region (8° 32' 19.37" N, 79° 52' 30.57" E–8° 32' 24.93" N, 79° 52' 27.81" E). Since it is a prominent headland area consisting of a sandy and gravel shoreline, it undergoes seasonal changes, including loss and accumulation (Gillie 1997).

3.1.1 Average Rates of Shoreline Change

When considering the total average EPR in each district, as Figure 6 shows, the Kalutara district recorded the highest rate of shoreline erosion (–1.21 ± 0.04 m/yr) and the Wilpattu region recorded the highest rate of accretion (0.95±0.58 m/yr). Unlike the Kalutara district, the Colombo and Gampaha districts also recorded changing erosion rates. However, Puttalam district had a changing accretion rate.

Figure 6: Average Rate of the Shoreline Changes in each Selected Area



The authors compared this result with the average shoreline change rates in each district before the year 2000, before the tsunami disaster, according to the statistics that the Ministry of Forestry and Environment published. When comparing the present data derived after the tsunami with these data from before the tsunami, Kalutara district showed a slight average accretion rate before the year 2000. Within the last 15 years, the average erosion rate has increased enormously. The present study revealed that the erosion rate in Colombo and Gampaha districts have also increased when compared with the erosion rate before 2000. However, the study could not identify any prominent change in the average coastal dynamic rate of Puttalam district.

Table 4: Comparison of the Data on Coastal Changes (Average Values) in Each District by the Years 2000 and 2019

Province	District	Erosion (-)/Accretion (+) Rates by 2000 (m/yr)	Erosion (-)/Accretion (+) Rates by 2019 (m/yr)
Western	Kalutara	0.1–0.4	–1.21
	Colombo	0.0–0.1	–0.54
	Gampaha	0.9–1.0	–0.7
North-Western	Puttalam	0.2–0.4	0.26

Source: Statistical Compendium on Natural Resources Management Sri Lanka 2000, Ministry of Forestry and the Environment.

The increasing coastal erosion rate in Kalutara, Colombo, and Gampaha after 2000 may have caused the destruction of natural barriers, like corals, and protective vegetation, like mangroves, due to the vast destructive phenomenon of the tsunami (Pattiaratchi 2005; Devi and Shenoi 2012), and, over time, different development projects have carried out physical alteration of the shoreline within the past 15 years (Figure 12).

To conserve the coastal zone, the CC and CRMD of Sri Lanka built hard protective structures with the collaboration of other reputable organizations. These structures provided a temporary solution to coastal erosion by preventing the degradation of the beach (Pranzini and Williams 2013). According to Silva et al. (2014), hard protection structures are the main coastal management strategy to mitigate the effect of coastal erosion in Latin American countries, in European countries, and on the Caribbean coast of Colombia.

However, this is not a sustainable solution because the structures tend to move the erosion along the coastal zone due to the effect of longshore sediment transport (Rangel-Buitrago, Williams, and Anfuso 2018). When considering the Kalutara, Colombo, and Gampaha districts in the Western province, Colombo applied more hard techniques along the coastal zone than the other two districts (Table 8). Since the majority of them are revetments and breakwaters of the Port City project and Colombo's commercial harbor, they may cause an increasing erosion rate in the other two districts due to the effect of longshore sediment transportation and seasonal winds.

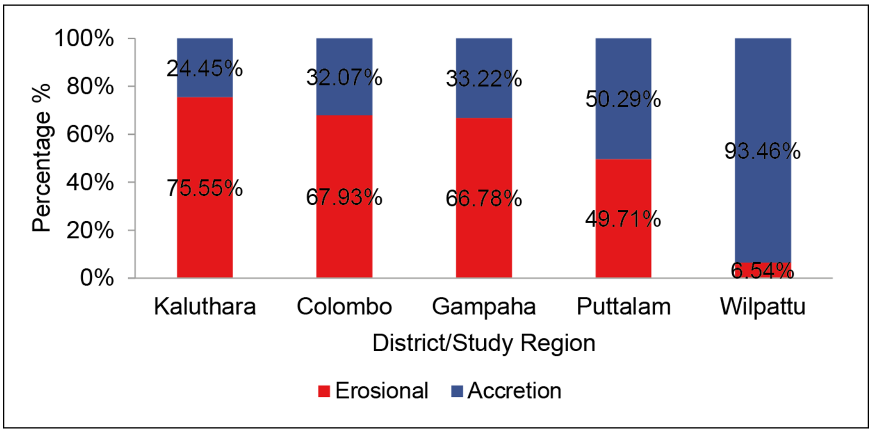
Furthermore, the application of hard structures has negatively affected the coastal scenery, and many beaches with high tourism potential now have little scenic value. The negative visual impacts are the result of the environmental degradation associated with the construction of hard protection structures and the collection of coastal debris (Williams and Micallef 2011; Rangel-Buitrago, Correa, Anfuso, Ergin, and Williams 2013; Williams et al. 2018)

The Puttalam district (within the Wilpattu region) shows accretion and few influences of anthropogenic activities, like the Western province, and the Wilpattu region behaves naturally, so it tends to maintain a stable environment rather than suffering from high erosion or accretion.

3.1.2 Percentage of Erosion and Accretion in Each Selected Area

As Figure 7 represented, erosion has strongly influenced the highest percentage (75.55%) of shorelines in the Kalutara district (approximately three-fourths of the Kalutara coast suffered erosion) and the Wilpattu region recorded the smallest area of erosion, with a high accretion percentage (93.46%) of the shoreline. Relative to the above rates of erosion and accretion (Figure 6), these results represent the same eroded and accreted percentages.

Figure 7: Percentage of Erosion and Accretion in Each Selected Area



Comparing the present data with the data from before the year 2000 revealed that Kalutara and Puttalam were stable, with the same range of erosion and accretion percentages (Table 5). However, Colombo and Gampaha experienced extraordinary erosion percentages. These fluctuations could be due to the above-mentioned reasons. Simply, if the rate of shoreline changes increases, the percentage of shoreline changes increases and vice versa.

Table 5: Erosion and Accretion Percentage Data Comparison in the Years 2000 and 2019

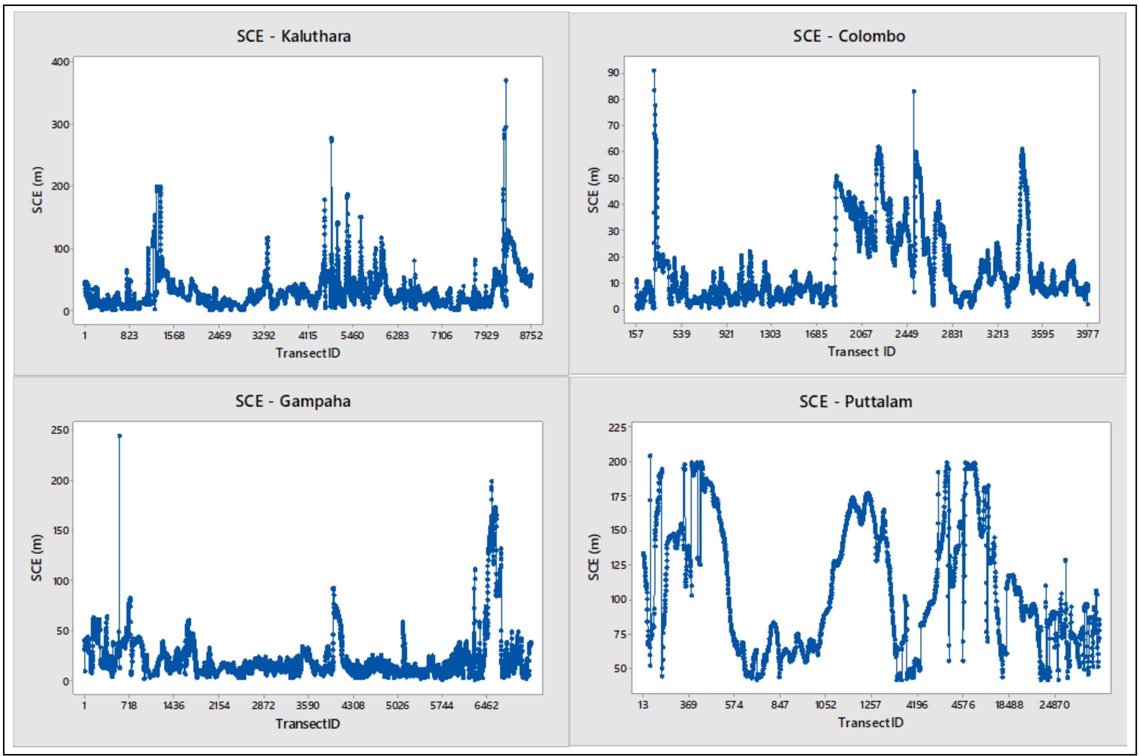
		2000		2019	
Province	**District**	**Erosion Percentage** (%)	**Accretion Percentage** (%)	**Erosion Percentage** (%)	**Accretion Percentage** (%)
Western	Kalutara	70–80	20–30	75.55	24.45
	Colombo	20–25	n.a.	67.93	32.07
	Gampaha	45–50	10–20	66.78	33.22
North-Western	Puttalam	30–40	30–60	49.71	50.29

Note: n.a. = not available.

Source: Statistical Compendium on Natural Resources Management Sri Lanka, Ministry of Forestry and Environment.

The comparison of the two districts with the greatest erosional changes (Kalutara) and the greatest accretion changes (Puttalam), using the SCE statistical data of Kalutara, showed that the maximum of 368 m accretion during the period 2010 to 2019 occurred in Kaluwamodara-West region (6°33'50.09"N, 79°59'14.93 E–6°26'7.31"N, 79°59'27.92"E) and the least dynamic shoreline, with a minimum of 0.76 m accretion from 2005 to 2015, was in Pothupitiya-West region (6°38'7.52"N, 79°56'13.17"E–6°37' 55.45"N, 79°56'17.75"E). Kaluwamodara-West region's considerably higher accretion level may be due to freshwater discharging from the Benthota River. The visual observations indicated that sand and mud particles that washed away from the inner land formed deposits around this estuary, so the seaward movement of land is apparent.

Figure 8: Graphical Representation of the SCE of Kalutara, Colombo, Gampaha, and Puttalam Districts



The SCE of Puttalam district indicated that the coastal zone of Puttalam has a stable and accretional beach with a low level of erosion. The upper part of the Kalpitiya peninsula showed a comparatively high erosion rate and high shoreline movement, including accretion and erosion. Further, the study identified this area as a critical region based on the large shoreline movement. According to Samanmali, Piyadasa, and Wickramasinghe (2014), a 32 m/yr shoreline change occurred from 1973 to 2014 in the Kandakuliya and Kudawa regions. Further, the shoreline change varied between 32.3±7.50 m/yr and –39.91±7.50 m/yr along the Kalpitiya region (Kandakuliya–Kudawa). These two results coincide and could be due mainly to natural phenomena, the sea-level rise, and the adverse effects of climatic change. All the aquatic ecosystems will be susceptible to variation of inundation, and coastal erosion and alterations in coastal ecosystems may lead to the sea level rising (Nianthi and Shaw 2015). The sea level rise in Sri Lanka was 0.3 m by 2010, and forecasts indicate that the sea level will rise by 1.0 m by 2070 (NATCOM 2000). It will also lead to increased coastal erosion in the coastal zone of Sri Lanka (Nianthi and Shaw 2015).

The ground truth investigation reported considerable human interventions, like fisheries and agriculture, and some agro-economic activities, and, according to Samanmali, Piyadasa, and Wickramasinghe (2014), regarding the "sea level rise and its impacts on Kalpitiya peninsula" in 2019, the coastal area of Kalpitiya peninsula is prone to many coastal hazards and sea level rise, and coastal erosion is related to the natural process of the climate, such as the wind direction, wind speed, and wave speed. Furthermore, Senevirathne et al. (2017) mentioned that coastal changes mainly occur when wind, waves, and longshore currents carry sand from the shore and deposit it somewhere else.

3.1.3 Shoreline Change Statistics

The study based the overall shoreline change statistics on the four digitized shorelines under the average NSM, EPR, and SCE with their standard deviations (SD) and the maximum and minimum values (Table 6 and Table 7). Here, the Kalutara district represents the highest erosional conditions with net shoreline erosion of –16.84±3.05 m and an average erosion rate of –1.21±0.04 m yr^{-1}. However, the Puttalam district represents accretional conditions than other districts.

Table 6: Summary of Shoreline Change Statistics

District	NSM±SD	EPR±SD	SCE±SD
Kalutara	–16.84 ± 3.05	–1.21 ± 0.04	30.97± 2.95
Colombo	–7.32 ± 1.58	–0.54 ± 0.63	15.67± 1.45
Gampaha	–9.82 ± 2.91	–0.7 ± 0.58	22.3 ± 2.46
Puttalum	5.12 ± 4.96	0.26 ± 0.07	38.23 ± 4.57

Table 7: The Maximum and Minimum Shoreline Change Statistics (SCS) for Selected Areas

District	SCS	Max.	Transect ID	Region	Min.	Transect ID	Region
Kalutara	EPR	24.47	8,291	Kaluwamodara-West	–19.06	5,071	Kalutara-South (Katukurunda)
	NSM	341.71	8,291	Kaluwamodara-West	–266.84	5,071	Kalutara-South
	SCE	368.79	8,291	Kaluwamodara-West (2010–2019)	0.76	2,875	Pothupitiya-West (2005–2015)
Colombo	EPR	4.29	2,518	Wedikanda-North	–1.93	2,445	Mount Lavinia
	NSM	47.89	1,877	Dehiwala North	–26.98	2,445	Mount Lavenia
	SCE	61.25	3,419	Angulana (2015–2019)	1.1	1,862	Dehiwala
Gampaha	EPR	15.47	570	Daluwakotuwa Beach	–6.03	6,571	Near Dikowita Harbor
	NSM	216.62	570	Daluwakotuwa Beach	–198.87	6,691	Near Dikowita Harbor
	SCE	244.14	570	Daluwakotuwa Beach (2005–2015)	0.76	5,742	Wahatiyagoda Beach (2010–2015)
Puttalam	EPR	32.3	1,432	Kudawa	–39.91	4,627	Kandakuliya
	NSM	199.95	1,418	Kudawa	–199.89	424	Kalpitiya (Upper)
	SCE	214.53	17,143	Chilaw (2005–2015)	0.59	20,847	Iranawila Beach (2015–2019)

The results show that considerably more erosion takes place in the Kalutara, Colombo, and Gampaha districts' coastal zones than in the Puttalam coastal zone. Therefore, these shoreline changes can be due mainly to the various development activities causing physical alterations of shorelines, seasonal changes, other anthropogenic interventions, and the effect of the applied hard coastal protective structures. The highest erosion rate is apparent around the Kalutara coast. In the estuary (Kaluganga estuary), the freshwater output of Kaluganga has washed away all the sandbars and eroded a vast area of the beach in Kalutara North (Calido beach, Kalutara). According to the ground truth investigation, this is a result of the rough seas due to the south-west monsoon in the last few years.

The study found that there is an unstable coastal zone all along the Colombo coast, but the Mount Lavenia and Wellawatta beaches showed moderate erosion. The coast, including Dehiwala, Mount Lavenia, and Wellawatta beaches, in the Colombo district showed severe seasonal erosion, mainly during the southwest monsoon (Lakmali et al. 2017). According to that study, the erosion along the coast including Dehiwala, Mount

Lavenia, and Wellawatta beach is not a permanent feature. The effect of erosion varies only seasonally and accretion occurs with the onset of the fair-weather north-eastern monsoon. Colombo, as the capital of Sri Lanka, has experienced strong anthropogenic interventions and alterations of the coastal zone due to the expansion and development of the city. Port City, combined with the Colombo south harbor project, was the major development activity causing physical alterations of the shoreline in Colombo. Within the past few years, it may have caused the highest erosion and accretion rates around Port City. The coastal area of Colombo has adopted many hard protection techniques (Table 8), so the observed erosion along most of the Colombo coast is not permanent. Lakmali et al. (2017) reported that the seasonal changes recover and accretion occurs after the rough season. Therefore, there is a stable condition or dynamic equilibrium in the present day and no long-term erosion is observable.

According to the results represented, there is also a considerably stable beach all around the Gampaha coast. The past data recorded that the erosion has affected the Uswatakeiyawa and Negombo coastal areas of Gampaha district moderately. Even though the areas have already introduced coastal protection techniques, erosion is still apparent here. The community in the area and the responsible fishery associations of Sri Lanka have accused the construction of the Port City project of causing this aggravated erosion. However, according to the data that the Marine Environment Protection Authority (MEPA) and the Coast Conservation and Coastal Resource Management Department (CC and CRMD) collected, there is no scientific proof of the effect of the Port City on coastal erosion (Gunawansa 2018). Nevertheless, according to Beaven et al. (2018), landfills are a major issue in shoreline management planning (SMP), which aims to manage the risks associated with flooding and coastal erosion.

Figure 9: Near-Shore Sediment Transportation Directions

Source: Long-term coastal erosion and shoreline positions of Sri Lanka (Lakmali et al. 2017).

In addition, the sediment deposition pattern associated with breakwaters and groynes in the entire area shows sand transportation predominantly toward the north (Figure 9). According to Lakmali et al. (2017), sediment deposition in the northern section characterizes the south-western coastal area, whereas erosion characterizes the southern section, implying predominant sediment transportation toward the north. Therefore, the south-western monsoon winds, which power the northerly-directed longshore transport, predominantly governs the south-western coastal belt.

When comparing the topographical characteristics of each site that recorded the largest erosion changes and largest accretion changes, it became apparent that most of the sites have a significant feature that causes their shoreline behavior. The Kaluwamodara region, which has the highest EPR in the Kalutara district, is adjacent to the Bentota River estuary. Here, the washed particles from the inner land can form deposits around the estuary, causing accretion changes in the area. The Mount Lavinia site with a low EPR in Colombo district and the Dikowita site in Gampaha, which also has a low EPR, have adjoined hard structures. Furthermore, the Dikowita site is very near to the Dikowita harbors. Sandy beaches completely cover the Kudawa and Kandakuliya sites. Due to the minimum human interventions in this region, the behavior of wind, waves, and longshore currents tend to move sand from one place to another. Finally, these areas have faced instant shoreline changes.

3.2 Application of Coastal Protective Constructions

The main hard coastal protective constructions that this study considered are revetments, breakwaters, coves, and groynes.

Figure 10: Categorized Hard Structures in the Study Area: (A) Revetments, (B) Breakwaters, (C) Coves, and (D) Groynes

Source: Breakwaters and cove images from GE imagery.

In the current study, areas have mainly implemented revetments as a coastal protective structure up to 23,554 m length (9.05%), covering 18,960 m in the Western province and 4,594 m in the North-Western province. The revetment is in the land ward margin of the boundary between the sea and the land, and the parallel structure reduces the wave action using solid durable structures, such as granite boulders. Areas have commonly used revetments to protect soft landforms, dunes, and coastal slopes to provide additional protection to address the erosion hazards. The protective effect of a revetment depends on the coastal area that implements it.

The extents of the coastal revetment in Kalutara, Colombo, Gampaha, and Puttalam districts were approximately 7,133 m, 9,432 m, 2,395 m, and 4,594 m, and their coverage percentages of the total coastal length were 16.85%, 38.81%, 6.90%, and 2.88%, respectively. The high net erosion rate that the Kalutara district recorded caused the implementation of a considerable extent of coastal revetments.

The total constructed lengths of breakwaters in the above districts, respectively, were 1,903 m, 702 m, 2,175 m, and 4,141 m. The total numbers of groynes in those districts were 19, 2, 29, and 91, respectively. According to the results, there were three coves in Kalutara, no coves in Colombo and Gampaha, and two coves in Puttalam at the end of 2019.

Table 8: Total Hard Structures in Kalutara, Colombo, Gampaha, and Puttalam Districts

Kalutara					Colombo				
Year	**BW** (m)	**Rvts** (m)	**Groynes**	**Coves**	**Year**	**BW** (m)	**Rvts** (m)	**Groynes**	**Coves**
2005	1,125.4	3,494.5	12	3	2005	1,045.1	8,804.7	1	
2009	1,198.1	3,515	10	3	2009	725.4	9,373	3	
2014	1,256.9	4,944.1	10	3	2014	493.6	10,401.2	2	
2019	1,902.9	7,132.7	19	3	2019	701.9	9,432.3	2	
Gampaha					**Puttalam**				
Year	**BW** (m)	**Rvts** (m)	**Groynes**	**Coves**	**Year**	**BW** (m)	**Rvts** (m)	**Groynes**	**Coves**
2005	1,911.3	2,924.4	20	1	2005	463.4	4,517.3	19	2
2009	1,674.6	3,505.6	24		2009	469.8	4,492	19	2
2014	1,784.5	2,921.3	25		2014	2,944.5	4,746.6	36	2
2019	2,175	2,394.5	29		2019	4,151.3	4,593.5	91	2

At the end of 2019, Puttalam district specifically, on the Kalpitiya peninsular, applied a vast amount of different hard structures: revetments and groynes. The unconsecrated sand layer around the Kalpitiya peninsular has suffered from a high erosion rate.

In 2005, the greatest application of hard structures took place within Colombo district. However, the Port City development project caused this application to decrease from 2014 to 2019 because of the removal of the hard structures around the region that covered the Port City in Colombo and the damage to the revetments in certain places.

Furthermore, other districts have gradually increased the application of hard structures over time. According to Figure 6, Kalutara and Gampaha have average erosion rates, so they have applied hard structures as precautions. In the Puttalam district, there is an average accretion rate, but Puttalam has implemented a huge number of hard structures to prevent adverse changes to the shoreline in certain regions. As an example, the region from Maha-oya estuary, Wennappuwa, Marawila, to Chilaw (7°16'42.39"N, 79°50'27.75"E–7°3'4.83"N, 79°47'24.85"E) applied an enormous amount of protective structures with a groyne series consisting of 38 individual groynes and a series of breakwaters with revetments (Rathnayakage et al. 2020). When comparing the applied hard structures in each district, all four districts have used revetments extensively while using coves minimally.

Anon (1997) mentioned the length of the existing effective shoreline protection works in 1996 for revetments and groynes as follows. When comparing this with the data for 2019, it showed that there was greater application of coastal structures in 1996 than in 2019 (revetments). The reduction of structures may be due to the destruction occurring over time, removal due to developments, disappearance, or due to the beach filling following accretion and the tsunami phenomenon in 2004.

Table 9: Data Comparison of Applied Hard Structures in 1996 and 2019

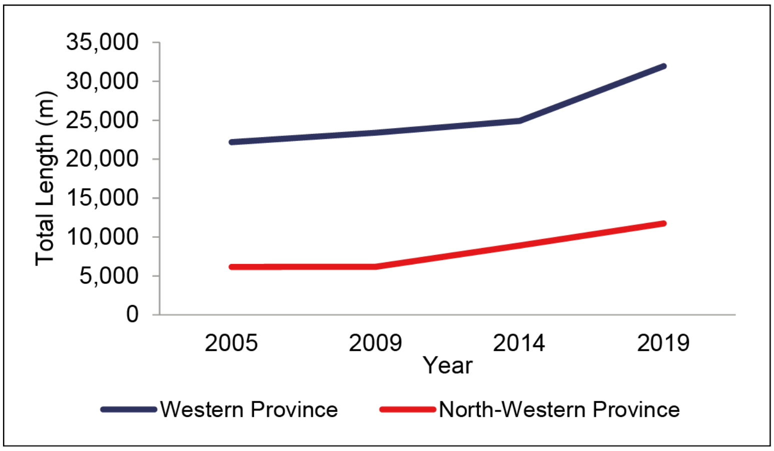
Coastal Region	**Total Length** (m) **1996**	**Total Length** (m) **2019**
Revetments West Coast (Gampaha, Colombo)	5,633	11,827
Groynes West Coast (Gampaha, Colombo)	2,135	6,309

Source: Anon (1997) (Coastal Area Management in Sri Lanka).

According to the National Action Plan for Protection of Marine and Coastal Environment from Land-Based Activities (1999), revetments provide protection to the length of the coastline that they cover, and their cost-effectiveness is greater than that of other hard structures.

Figure 11 proves that the Western province has implemented a larger amount of coastal protection techniques to conserve the coastal zone than the North-Western province. This conservation method is based entirely on utilization, humans' alterations of the shoreline, and the adverse effects of natural phenomena. The Western province (Colombo, Kalutara, and Gampaha) has utilized its coastal zone more to for development projects, the tourism industry, residences, infrastructure, and so on than the North-Western province. To some extent, there has been minimal human influence along the North-Western province's shoreline, so there is a naturally behaving sandy beach up to Kalpitiya peninsula.

Figure 11: Total Hard Structures in the North-Western and Western Provinces



3.2.1 Influence of the Protective Structures on the Beach

This section elaborates on the shoreline changes that have occurred in three different scenarios, namely within the site close to the structure, adjacent to the structure to 1 km away, and 5 km away from the structure.

Table 10: Shoreline Changes in the Study Area with Respect to Applied Hard Structures

	At the Site			Adjacent to the Site (1 km Away)			Away from the Site (5 km Away)		
Structure	**NSM**	**EPR**	**SCE**	**NSM**	**EPR**	**SCE**	**NSM**	**EPR**	**SCE**
G1	20.39	1.46	22.54	31.61	2.26	31.61	0.21	0.02	22.19
G2	–11.47	–0.82	20.73	–1.66	–0.12	10.11	9.29	0.66	9.29
G3	–6.33	–0.45	6.33	–12.62	–0.9	18.64	–3.29	–0.23	14.49
G4	–4.05	0.29	12.13	–34.07	–2.43	34.07	1.79	0.13	8.38
G5	–24.1	–1.72	24.1	–8.43	–0.6	22.55	27.25	1.95	39.48
BW1	15.04	1.07	15.04	–59.55	–4.25	63.12	8.15	0.58	19.94
BW2	90.72	6.48	92.23	–17.28	–1.23	18.28	0.94	0.07	10.93
BW3	19.89	1.42	20.41	4.3	0.31	12.12	6.29	0.45	7.47
BW4	10.11	0.72	10.11	–12.23	–0.87	12.72	–20.11	–1.44	25.53
BW5	–4.84	–0.35	8.41	11.08	0.79	11.08	–46.7	–3.34	47.38
R1	–6.11	–0.44	9.02	–9.53	–0.68	9.53	11	0.79	18.34
R2	9.03	0.64	9.03	–2.78	–0.2	3.38	0.11	0.01	1.92
R3	–8.66	–0.62	12.14	–35.49	–2.53	35.49	–1.67	–0.12	4.08
R4	–11.8	–0.84	11.8	–26.2	–1.87	32.89	–27.42	–1.96	29.59
R5	3.01	0.22	13.66	11.09	0.79	11.27	–26.71	–1.91	35.58

Note: G: Groynes, BW: Breakwaters, R: Revetments.

Table 10 shows certain shoreline changes in and related to the randomly selected hard protective structures in the study area. When considering the shoreline changes within the selected site, it is possible to categorize them into the rates of low erosion (–1.0<EPR≤–0.5), stable condition (–0.5<EPR≤0.5), low accretion (0.5<EPR≤1.0), and occasionally high accretion around the selected hard structure. The NSM also shows low erosional movements and accretion movements at the site. The shoreline change variability (SCE) represents more accretional movements than erosional movements. When comparing the shoreline change rates of groynes, breakwaters, and revetments within the site, it is apparent that there are only stable and accretion rates around the breakwaters and there are accretion shoreline movements other than around groynes and revetments.

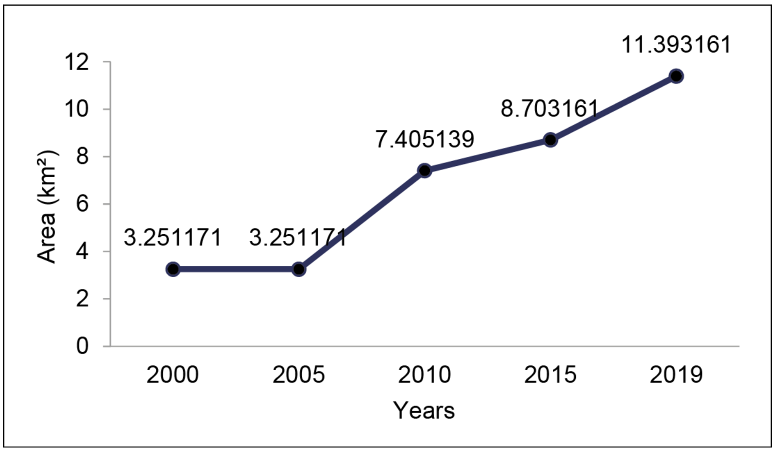
All the EPR changes adjacent to the selected site (1 km) and 5 km away have low erosion (–1.0<EPR≤–0.5), stable condition (–0.5<EPR≤0.5), and low accretion (0.5<EPR≤1.0) rates, with moderate and high erosion occurring rarely. In addition, it is possible to identify the NSM of each site as low erosional movements and low accretional movements. The hard structures, like groynes and breakwaters, are good for the site but not much better for the adjacent area. The current study does not fully describe the direct relationship between the coastal protective structures and the shoreline changes, but there is a minimal effect from the hard structures on the shoreline changes because somewhat controlled changes are apparent to a certain extent. However, regarding the original purpose of applying hard structures, they have

not achieved the same success as examples elsewhere in the world (Rangel-Buitrago, Williams, and Anfuso 2018).

3.3 Coastal Development through Physical Alteration of the Shoreline

The data in Figure 12 represent areas' execution of coastal developments causing physical alteration of the shoreline over the past 20 years within the Western and North-Western provinces. There are five main harbors and a landfilling area that developed from altering the shoreline in the study area. The Colombo harbor, the fishery harbor in Colombo, and the Beruwala fishery harbors have existed from the early 2000s up to the present in the Western province. From 2009 to 2011, a small harbor was located in Pothupitiya, Kalutara. The governing body selected this area as a suitable coastal stretch, extending over a 72,000 m^2 area, for siting the temporary quarry rock loadout point (LoP) for the transshipment of rock to Colombo. It has finished the construction of a temporary breakwater extending over 500 m and a seafront wall and has been undertaking the dredging of the basin since October 2008 (Lee et al. 2010). It established the Dikowita fishery harbor and Colombo south harbor in 2010 and a huge area incrementation in Colombo south harbor by 2019 by expanding the wave breaks to protect the harbor. Furthermore, the mass artificial landfilling project "Port City" commenced in 2015 and has now expanded over 269 ha as an additional part of Sri Lanka in Colombo district.

Figure 12: Coastal Development by Physical Alteration of the Shoreline within the Past 20 Years



This graph shows the increase in areas of coastal developments from 2000 to 2019.

Finally, this study has helped to prove that all these human influences or anthropogenic interventions have caused shoreline changes directly or indirectly in this study area. In addition, there is an effect of natural phenomena, like tidal variations, sea-level rises, storm surges, and so on. These two causes are interconnected. If highly adverse activities occur around the coastal zone, they cause adverse behaviors of the sea, and the aggravated behaviors of the sea tend to increase the human influence on the coastal zone. Therefore, it is important to study the dynamic nature of the shoreline with respect to wind patterns, current patterns, sea-level rises, and natural barriers, which help to protect the coastal zone.

4. CONCLUSIONS

The findings highlighted that the part of the study area experiencing coastal erosion due to anthropogenic activities may face more drastic changes in its shoreline and environment than other areas in the Western and North-Western regions of Sri Lanka. Therefore, anthropogenic activities are the leading factor in coastal erosion in the respective study area rather than natural scenarios such as a sea-level rise, climatic changes, and natural disaster conditions. The application of hard structures is the solution that is least able to control coastal erosion in a large area because applying hard structure is good for the site but not very helpful for other adjacent areas. Therefore, as long as humans introduce no alterations, the environment will remain under its natural conditions. If the shoreline is changing naturally, as humans, we have to adjust rather than alter it. Furthermore, proper identification of the dynamic nature of the shoreline that is occurring due to the behavior of wave patterns and coastal currents, obligatory subsidies for the conservation and management of the coastal zone, buffering capacity from natural coastal ecosystems, and coastal-based industries are very important. This study may provide information regarding where and when ad hoc coastal zone development projects and ad hoc soft and hard coastal conservation programs will work effectively within the coastal zone.

4.1 Limitations of the Study

The authors based this study on the analysis of GIS and remote sensing data. Basically, the digitization relied on visual interpretations, and errors can occur in the final results if the remotely sensed data do not undergo correct preprocessing. Insufficient previous data and studies regarding shoreline changes in this area were available to carry out a comparative study.

4.2 Recommendations for Future Research

This research mainly focused on the shoreline changes and the effect of human influences and natural phenomena on the Western and North-Western provinces' coasts. Further study could identify the changes along the whole coastline of Sri Lanka and establish a proper mechanism to define the predictability and the dynamic nature of the shoreline and the effect of a sea-level rise, the current patterns, and the wind patterns on the shoreline. The findings of further studies can assist in revising the coastal management plan to ensure effective management approaches.

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